

# Infrared Observations of the Candidate LBV 1806-20 & Nearby Cluster Stars<sup>1,2,3</sup>

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## ABSTRACT

We report near-infrared photometry, spectroscopy, and speckle imaging of the hot, luminous star we identify as candidate LBV 1806-20<sup>1</sup>. We also present photometry and spectroscopy of 3 nearby stars, which are members of the same star cluster containing LBV 1806-20 and SGR 1806-20. The spectroscopy and photometry show that LBV 1806-20 is similar in many respects to the luminous

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<sup>1</sup>We note that this star has not been observed to undergo a major LBV outburst yet, and thus some may not consider it to be an LBV (though it is undoubtedly luminous, blue, and variable, and shares many spectral characteristics with *bone fide* LBV stars, as we show here). Hereafter, to avoid awkward phrasing, we refer to the candidate LBV as LBV 1806-20 as is done in the literature.

“Pistol Star”, albeit with some important differences. They also provide estimates of the effective temperature and reddening of LBV 1806-20, and confirm distance estimates, leading to a best estimate for the luminosity of this star of  $> 5 \times 10^6 L_{\odot}$ . The nearby cluster stars have spectral types and inferred absolute magnitudes which confirm the distance (and thus luminosity) estimate for LBV 1806-20. If we drop kinematic measurements of the distance ( $15.1^{+1.8}_{-1.3}$  kpc), we have a lower limit on the distance of  $> 9.5$  kpc, and on the luminosity of  $> 2 \times 10^6 L_{\odot}$ , based on the cluster stars. If we drop both the kinematic and cluster star indicators for distance, an ammonia absorption feature sets yet another lower limit to the distance of  $> 5.7$  kpc, with a corresponding luminosity estimate of  $> 7 \times 10^5 L_{\odot}$  for the candidate LBV 1806-20. Furthermore, based on very high angular-resolution speckle images, we determine that LBV 1806-20 is not a cluster of stars, but is rather a single star or binary system. Simple arguments based on the Eddington luminosity lead to an estimate of the total mass of LBV 1806-20 (single or binary) exceeding  $190 M_{\odot}$ . We discuss the possible uncertainties in these results, and their implications for the star formation history of this cluster.

*Subject headings:* stars: early type — stars: emission-line — stars: Wolf-Rayet — stars: supergiants — infrared: stars — open clusters and associations: general

## 1. Introduction

Mounting evidence gathered in recent years indicates that stars may be formed with masses much greater than previously thought possible. The hot luminous “Pistol Star” near our Galaxy’s center, for instance, has an estimated mass of  $> 150 M_{\odot}$  (Figer et al. 1998), and the stars R136a1 and R136a2 in the Large Magellanic Cloud each have masses of  $140 - 155 M_{\odot}$  (Massey & Hunter 1998). Since the luminosities of such massive stars exceed  $10^6 L_{\odot}$ , relatively small populations of these stars can dominate the power output of their host galaxy during their lifetimes. Furthermore, their deaths may spread chemically-enriched material into the galaxy and leave behind black holes as remnants. The death events may be responsible for gamma-ray bursts in the “collapsar” scenario (e.g. Price et al. (2003); Hjorth et al. (2003); Macfadyen et al. (2001)), and the relatively large remnant black holes may also explain the so-called “intermediate-mass” black holes currently being discovered in nearby galaxies (e.g. Kaaret et al. (2001) and references therein). Thus, probing the upper limit for stellar mass has an important impact on our understanding of a wide range of astrophysical phenomena, including the chemical evolution of matter in our Galaxy and external galaxies,

the history of galaxy and structure formation in the Universe, the formation of black holes in their dying supernova events, and possibly the origin of gamma-ray bursts via collapsars.

We report here new observations of a luminous star we identify as LBV 1806-20. This star was first identified as a potential counterpart to the soft gamma-ray repeater SGR 1806-20 (Kulkarni et al. 1995), with high near-infrared brightness ( $K = 8.4$  mag) despite significant absorption from interstellar dust in the Galactic Plane. Subsequent moderate-resolution ( $R \sim 700$ ) infrared spectroscopy revealed it to be a candidate luminous blue variable (LBV) star and one of the most luminous stars in the Galaxy, with  $L > 10^6 L_{\odot}$  (van Kerkwijk et al. (1995) ; Corbel et al. (1997)). This star is known to lie at the brightness peak of the radio nebula G10.0-0.3 (Kulkarni & Frail (1993); Vasisht et al. (1995)). However, the revised Inter-Planetary Network (IPN) localization of SGR 1806-20 indicated that the SGR was significantly offset from the position of the candidate LBV star and the coincident core of G10.0-0.3 (Hurley et al. 1999). Recent *Chandra* and infrared observations confirm that the SGR lies  $\sim 12''$  away from the candidate LBV (Kaplan et al. (2002); Eikenberry et al. (2001)). In addition, Gaensler et al. (2001) show that G10.0-0.3 is not a supernova remnant at all, but is a radio nebula powered by the tremendous wind of the candidate LBV star at its core. The apparent conundrum presented by this scenario – why we find two such rare objects so close to each other on the sky without any apparent physical connection – has been resolved by the observations of Fuchs et al. (1999) who showed that LBV 1806-20 is a member of a cluster of massive stars, and of Eikenberry et al. (2001) who showed that SGR 1806-20 appears to be a member of the same cluster. Thus, while these two rare objects are not identical, they are related through common cluster membership. Interestingly, Vrba et al. (2000) show that one of the other SGRs in the Milky Way may also be associated with a massive star cluster.

The distance to the candidate LBV, SGR, and their associated cluster has also been a subject of some discussion in the literature. Initial studies of CO emission from molecular clouds towards this line of sight and the detection of  $\text{NH}_3$  absorption against the radio continuum indicated an extinction of  $A_V = 35 \pm 5$  mag and a best estimate for the distance of  $14.5 \pm 1.4$  kpc (Corbel et al. 1997) – again confirming its status as one of the most luminous stars known. However, Blum et al. (2001) present infrared spectra of members of a cluster in the nearby H II region G10.2-0.3, which is also part of the (apparent) W31 giant molecular cloud complex containing G10.0-0.3, and find an apparently conflicting distance of  $\sim 3.4 \pm 0.6$  kpc. This apparent conflict has also been recently resolved by Corbel & Eikenberry (2003), who present higher-resolution millimeter and infrared observations of G10.0-0.3 and G10.2-0.3. They find that W31 is actually resolved into at least 2 components along the line-of-sight, with one component at  $d \sim 4$  kpc and with extinction  $A_V \sim 15$  mag (in excellent agreement with the Blum et al. (2001) observations of G10.2-0.3) and another

component at a (refined) distance of  $d = 15.1_{-1.3}^{+1.8}$  kpc and with  $A_V = 37 \pm 3$  mag. The radial velocity of LBV 1806-20 matches both of these components, but the  $NH_3$  absorption towards the core of G10.0-0.3 (and thus LBV 1806-20) due to a cloud at  $d = 5.7$  kpc unambiguously places the star in the “far” component of W31. In addition, both the infrared extinction towards LBV 1806-20 (van Kerkwijk et al. (1995); see also below) and the X-ray absorption column towards SGR 1806-20 (Eikenberry et al. (2001); Mereghetti et al. (2000)) match the expected extinction towards the “far” component of W31 and differ from that of the “near” component of Blum et al. (2001) by  $\sim 15$  mag, thus confirming the association of the candidate LBV, SGR, and associated star cluster with the “far” component of W31.

In order to further investigate this intriguing object, we obtained near-infrared images and spectra of LBV 1806-20 and several nearby stars. In Section 2, we describe these observations and their reduction. In Section 3, we describe the analysis of the resulting data, including the spectral types of the candidate LBV and cluster stars, refined analyses of the reddening, confirmation of the distance estimate of Corbel & Eikenberry (2003), and the resulting luminosity estimate for LBV 1806-20. In Section 4, we discuss the uncertainties in these measurements and their implications for our understanding of the formation and evolution of extremely massive stars and the birth environment of SGRs. Finally, in Section 5 we present our conclusions.

## 2. Observations and Data Reduction

### 2.1. CTIO – July 2001

We used the Ohio State InfraRed Imaging Spectrograph (OSIRIS) instrument (Depoy et al. 1993) and f/14 tip-tilt secondary on the Cerro-Tololo Inter-American Observatory (CTIO) 4-meter telescope on July 5-6, 2001 to observe LBV 1806-20 and nearby stars. In the OSIRIS imaging mode, we obtained  $J$ –,  $H$ –, and  $K$ –band images with a  $0.161''$  pixel $^{-1}$  plate scale. While conditions were non-photometric due to high clouds, the seeing conditions were acceptable when the transparency allowed observations – using the tip-tilt secondary, typical images had full-widths at half-maximum (FWHM) of  $\sim 0.6 - 0.7''$ . In each band, we obtained a set of 9 images in a  $3 \times 3$  raster pattern with a  $10''$  offset between images. We then subtracted dark frames from each image, divided the result by its own median, and then median-combined the resulting images into a normalized sky frame. We then subtracted the dark frame and a scaled version of the sky frame from each of the 9 images, and divided the result by a dome flat image. We shifted each of the 9 frames to a common reference position and added them to give a final summed image in each band. Figure 1 shows a composite 3-color image of the field of LBV 1806-20 in the following near-infrared bands:  $J = 1.25\mu\text{m}$

(blue);  $H = 1.65\mu\text{m}$  (green);  $K = 2.2\mu\text{m}$  (red).

We also used the OSIRIS high-resolution spectroscopic mode to obtain moderate resolution ( $R = 1500$  for a 4-pixel slit) spectra of LBV 1806-20 and three nearby stars (B, C, D in Figure 1). This group of stars, approximately  $12''$  west of LBV 1806-20 appears to be a cluster of young, hot, luminous stars in the same molecular cloud as, and including, the candidate LBV star (Fuchs et al. 1999). At the estimated distance of 15.1 kpc (Corbel & Eikenberry 2003), this angular separation corresponds to a physical distance of only  $\sim 1$  pc between the candidate LBV star and the center of the cluster, implying a common origin. Thus, we chose the three brightest stars near the center of the association for spectroscopic observation. We oriented the OSIRIS slit to obtain spectra simultaneously of LBV 1806-20 and Star B, and separately to obtain simultaneous spectra of Stars C and D. We used the high-resolution slit of OSIRIS (4 pixels =  $0.67''$ ), and took  $6 \times 120$ -s exposures at positions offset along the slit. After each set of 6 exposures, we obtained a set of 6 spectra of the nearby G dwarf star HR6998, with approximately the same positions along the slit. We repeated this approach for 2 different grating settings for each of the K and H bands, and one grating setting for LBV 1806-20 in the J-band. For both the science targets and the G-star, we took each spectral frame, subtracted a dark frame from it, divided by its own median, and median-combined the 6 resulting images for a given grating tilt to create a normalized sky frame. We then subtracted a dark frame and a scaled sky frame from each image and divided by a spectral dome flat. We extracted spectra separately from each processed image with a Gaussian weighting in the spatial direction and tracking the curvature of the spectrum in the dispersion direction. We then divided each target spectrum by the G-star spectrum with the nearest position on the slit to remove atmospheric absorption bands, after interpolating over the Brackett absorption features in the G-star spectrum. We obtained a wavelength solution separately for each spectrum using the OH lines nearby on the sky (typical residuals  $< 20 \text{ km s}^{-1}$  in velocity space), and used this to correct each spectrum to a common wavelength scale before averaging the spectra to a single final spectrum. For H and K bands, we averaged the 2 spectra from the different grating tilts where they overlapped. We multiplied the result by a 5600K blackbody spectrum (corresponding to the temperature of HR 6998), and de-reddened them for  $A_V = 29$  mag (see below for further discussion on the reddening). We present these spectra in Figures 2-6.

## 2.2. HBO – July 2001

Due to the non-photometric conditions during the CTIO observations, we were unable to photometrically zeropoint-calibrate the images obtained at that time. Thus, we post-

calibrated these images using observations of stars in the field of LBV 1806-20 and infrared standard stars on July 27, 2001 with the Hartung-Boothroyd Observatory 0.65-meter telescope and its infrared array camera (Houck & Colonna in prep.), as well as with photometry from the Two-Micron All-Sky Survey (2MASS). We took 7 images of the field of LBV 1806-20 in each band, with offsets of  $\sim 15''$  between images. We then processed the images in each band as described for the CTIO data above. We repeated this procedure on sets of 7 images of the UKIRT standard FS26 in each band. We extracted the flux in ADU/s from each processed image of FS26 individually, using the average as the best estimate of the flux, and the standard deviation divided by the square root of the number of exposures as the  $1\sigma$  uncertainty. We then used the known magnitudes of this star to calibrate similarly-derived flux measurements and uncertainties for several bright stars in the field of LBV 1806-20. Differential photometry between these stars and the target stars provided the final photometric measurements. We used a photometric airmass solution derived from measurements of a star observed for another program over a range of airmasses throughout the same night. We then verified this photometry with the 2MASS photometry for J and H band (omitting K, as 2MASS uses the  $K_s$  filter). We present the resulting photometry for the bright stars of Figure 1 in Table 1.

### 2.3. Palomar – July, 1999

We obtained high angular-resolution speckle imaging of LBV 1806-20 in June 1999 using the Palomar 5-meter telescope. We used the facility near-infrared camera D78 with reimaging fore-optics providing a pixel scale of  $0.036''(\pm 0.001'')$  per pixel to obtain K-band images of the star with 0.125s exposures, effectively freezing the effects of image motion due to atmospheric turbulence. We observed LBV 1806-20 in 6 sets of 50s on-target integrations, interleaved with observations of 2 nearby stars with similar near-infrared brightnesses taken in an identical manner. We used a “shift-and-add” technique to combine images of the individual stars – for each star (LBV 1806-20 and the 2 comparison stars) we shifted the images to align the brightest speckle in each frame with other frames and added the results. We used these nearby stars to create the model point spread function (PSF), which were seen to have FWHM of  $0.130''$  – near the telescope’s diffraction limit of  $0.110''$  at this wavelength. We then scaled the amplitude of this model PSF and subtracted it from the shifted-and-added image of LBV 1806-20. We also used Fourier filtering to remove a periodic diagonal pattern due to clocking noise in the camera electronics. Figure 7 shows an image of LBV 1806-20 and the resulting PSF-subtracted image. While the residuals in the subtracted image are statistically significant, they may be due to systematic effects, such as sub-pixel errors in image registration or secular small-scale variations in the speckle PSF, possibly due

to low-level instability in the time-averaged properties of the speckle halo. For comparison, we also show simulated PSF-subtracted images of a theoretical extended source with a very small size ( $0.06''$  FWHM). To simulate this source, we took the comparison star PSF and convolved it with a 2-D Gaussian profile with a width corresponding to the extended source intrinsic width. We then added noise corresponding to the photon noise in the LBV 1806-20 image to the resulting simulated image, and then subtracted a scaled version of the single-star PSF as above. Note that the resulting simulations have residuals much greater than those for the actual PSF-subtracted image.

### 3. Analysis

#### 3.1. Spectral Analysis

##### 3.1.1. *LBV 1806-20*

Based on the spectra in Figures 2-4, we present measured equivalent widths for emission and absorption lines from LBV 1806-20 in Table 2. The line features evident in the K-band spectrum of LBV 1806-20 (HI, HeI, FeII, MgII, NaI) are very similar to those observed in LBV stars such as AG Car (Morris et al. 1996), the Pistol Star in the Quintuplet (Figer et al. 1998), and the LBV candidate Star 362 also in the Quintuplet (Geballe et al. 2000) (and at lower resolution from this same star in 1994 (van Kerkwijk et al. 1995)). The equivalent widths of the FeII, MgII, and NaI features are very close also, though the HI and HeI lines are generally stronger in LBV 1806-20. P Cygni also displays a similar K-band spectrum (Smith 2001), although with an apparent absence of NaI emission. In the H-band, LBV 1806-20 seems like a cross between P Cygni and the Pistol Star, with 10 strong Brackett series lines and 9 FeII emission lines. While the Pistol Star and AG Car exhibit similar iron features, their Brackett series lines are much weaker than seen in LBV 1806-20. P Cygni, on the other hand, shows strong Brackett series with weaker FeII. Thus, while the spectrum of LBV 1806-20 does not uniquely match any particular LBV, its properties are well within the range exhibited by these stars. Thus, we conclude that based on its spectrum LBV 1806-20 is in fact a luminous blue variable candidate, in confirmation of van Kerkwijk et al. (1995).

The HeI  $2.112\mu\text{m}$  absorption line provides important information on the temperature of LBV 1806-20. In 1994, the equivalent width of this line was  $1.8 \pm 0.4 \text{ \AA}$  (van Kerkwijk et al. 1995), consistent with spectral classes O9-B2 of supergiant stars (Hanson et al. 1996), indicating a surface temperature of 18000 K to 32000 K <sup>2</sup>. The large range in temperature is

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<sup>2</sup>We note that it is conceivable that the temperature-EW relation for supergiants (which has rather large

due to the large scatter in this relationship (Hanson et al. 1996). By the time of the July 2001 observations, the equivalent width of the line had dropped to  $0.76 \pm 0.17 \text{ \AA}$ . Changes in the spectral type to hotter (O6.5-O8.5) surface temperature would produce such a reduction in the HeI absorption line equivalent width (Hanson et al. 1996). Moreover, at the same time, we see a factor of  $\sim 4 - 6$  increase in the equivalent width of emission lines such as  $\text{Br}\gamma$  and HeI  $2.058\mu\text{m}$ , which could reflect an increase in the number of ionizing photons produced by the star as it moved to higher temperatures. However, such a temperature change might also imply a significant brightening in the K-band (given a constant photospheric radius), contrary to the observations. In fact, our K-band photometry for LBV 1806-20 is marginally fainter than that of Kulkarni et al. (1995) ( $K = 8.4 \text{ mag}$ , with no quoted uncertainty). We can find an alternate solution which keeps the K-band brightness constant while decreasing the HeI absorption and increasing the number of ionizing photons, by assuming that the photospheric radius decreases significantly as temperature increases. Simple calculations for a blackbody spectrum show that a change of temperature from 20,000K to 26,000K (roughly B1.5 to B0) accompanied by a  $\sim 25\%$  decrease in photospheric radius could produce the observed behavior. Such anti-correlated variations in temperature and radius are characteristic of some LBV stars (Humphreys & Davidson (1996); Morris et al. (1996)). Alternately, the stronger lines might indicate an increase in the stellar wind density absorbing more ultraviolet continuum photons and converting them into increased line emission. However, without detailed models of the atmosphere of LBV 1806-20, we can only conclude that it has a spectral type between O9 and B2.

### 3.1.2. *Star B*

From the color of Star B in Figure 1, we can immediately see that it differs significantly from the other stars in the field due to its extreme redness ( $J - K = 7.3 \text{ mag}$  versus  $J - K < 6.0 \text{ mag}$  for other stars). In addition, the emission line spectrum (Figure 5) differs significantly from LBV 1806-20, showing relatively weak  $\text{Br}\gamma$  and strong blended emission from HeI, HeII, CIII, CIV, NIII, and NIV. This K-band spectrum is typical for late-type Wolf-Rayet stars of the WC subclass, and comparison of the equivalent widths of these lines with other similar stars (Figer et al. 1997) gives a classification of WC9. The long wavelength excess in the continuum indicates the presence of warm dust with a thermal continuum extending into the near-infrared – another common feature in WCL (late-type

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scatter) does not apply to candidate LBV stars. However, independent temperature measurements for the Pistol Star (Figer et al. 1998) are consistent with the temperatures derived from its HeI  $2.112\mu\text{m}$  absorption feature, indicating that this approximate relationship seems to continue to hold for candidate LBV stars.



WC) stars, and also explaining the very red colors of this object. We should note that only 26 such WCLd (dust emission) stars are known at this time (van der Hucht 2001), making this a rather rare star.

### 3.1.3. Stars C and D

The next brightest stars in the cluster center, C and D, have similar colors to LBV 1806-20, with  $J - K = 5.6$  mag and  $J - K = 4.9$  mag, respectively. In their K-band spectra, both stars show  $\text{Br}\gamma$  and  $\text{HeI } 2.112\mu\text{m}$  absorption features. They also seem to show some sort of feature at the  $\text{HeI } 2.058\mu\text{m}$  line. This could either be due to a self-absorbed (nascent P-Cygni) line, or else due to poor subtraction of a nearby strong OH sky line. Based on their strong  $\text{HeI } 2.112\mu\text{m}$  absorption lines, both of these stars would seem to have spectral classes in the range from B0 to B3 supergiants (Hanson et al. 1996). However, in both of these absorption lines, as well as the stronger of the Brackett series lines in the H-band spectra for these stars, we see some evidence for absorption wings (Figure 6). Fits to these lines give velocity widths of  $> 200\text{km s}^{-1}$  FWHM (after subtraction of the instrumental line widths), although some of these lines are potentially blended (particularly  $\text{Br}\gamma$  with nearby He lines). Such broad absorption wings are typical of the luminous blue hypergiants (luminosity class Ia+), and may indicate the presence of a mass-losing wind (de Jager 1998). Thus, we conclude (for the time being) that Stars C and D are B0-B3 supergiant or hypergiant stars.

## 3.2. The Reddening towards LBV 1806-20

The colors of LBV 1806-20 and its spectral continuum shape allow us to estimate the extinction towards LBV 1806-20. For such a hot star (as indicated by the  $\text{HeI } 2.112\mu\text{m}$  absorption feature), the intrinsic  $J - K$  color is nearly neutral, and the observed red color of  $J - K = 5.0 \pm 0.15$  mag corresponds to an extinction of  $A_V = 28 \pm 3$  mag (assuming the Rieke-Lebofsky reddening law (Rieke & Lebofsky 1985)), matching the estimates based on CO observations (Corbel & Eikenberry 2003). (While a hypothetical infrared excess from LBV 1806-20 would alter these conclusions, as we discuss below there is good reason to believe this is not present). Furthermore, the fact that stars C and D in the nearby cluster have very similar  $J - K$  colors (as can also be seen for many other cluster stars' colors in Figure 1) indicates that the stellar cluster is indeed at the same reddening and thus distance along the line of sight as LBV 1806-20, confirming the physical association between them (see also Eikenberry et al. (2001)). In addition, the H and K bands are in the Rayleigh-Jeans portion of the blackbody emission curve for such a hot star (the reason for the neutral colors

noted above). Thus, we can estimate the extinction towards LBV 1806-20 by de-reddening the spectra until the continuum shape matches a Rayleigh-Jeans distribution. In this way, we obtain estimates of  $A_V = 31 \pm 3$  mag from the H-band continuum and  $A_V = 28 \pm 3$  mag from the K-band continuum, with uncertainties dominated by  $\sim 10\%$  uncertainty in the spectrograph response shape over a given order.

For the  $J - K$  measurement above, adoption of the Cardelli reddening law (Cardelli et al. 1989) gives a very small change in  $A_V$  ( $< 0.4$  mag), and the K-band spectral continuum shape is similar unaffected (change of  $< 0.1$  mag). In the H-band, the Cardelli law differs from Rieke-Lebofsky more significantly, causing a difference of  $\sim 1.9$  mag. Taking this into account, we increase our uncertainty in that measurement to  $A_V = 28 \pm 4$  mag. Combining all three, we adopt a final estimate for the extinction of  $A_V = 29 \pm 2$  mag towards LBV 1806-20.

### 3.3. The Distance to LBV 1806-20

The distance to LBV 1806-20 is a major subject of Corbel et al. (1997) and Corbel & Eikenberry (2003), and we refer the reader to those papers for detailed discussion. In summary, Corbel et al. (1997) and Corbel & Eikenberry (2003) use CO spectroscopy to identify molecular clouds along the line-of-sight towards LBV 1806-20, and use the cloud velocities to determine kinematic distances to them. The spectra of LBV 1806-20 presented here provide important insights into the distance of the star. From the emission lines, we can measure a radial velocity of LBV 1806-20. We selected the Br $\gamma$  line as a velocity fiducial, as it is the strongest line detection in the spectrum, and appears to be relatively free from contamination due to blending with other strong lines. We fit a Gaussian profile to this line, finding no significant residuals, and a centroid shifted from the atmospheric rest frame by  $-3 \pm 20$  km s $^{-1}$ , where residuals in the spectral wavelength solution from atmospheric OH emission lines dominate the largely systematic uncertainty. After correcting for the Earth’s barycentric motion and the Solar System barycenter motion relative to the local standard of rest, we determine a radial velocity for LBV 1806-20 of  $v_{LSR} = 10 \pm 20$  km s $^{-1}$ . Cross-checks of this velocity determination with several other strong unblended lines give consistent results for the velocity of LBV 1806-20. This velocity is important, as massive stars such as LBVs are a kinematically “cold” population, and do not generally deviate significantly in velocity from their parent molecular clouds. Combined with the CO velocity maps of Corbel et al. (1997) and Corbel & Eikenberry (2003), this velocity then confirms the association of LBV 1806-20 with molecular clouds in W31 at kinematic distances of either  $\sim 4$  kpc or  $\sim 15$  kpc, based on the Galactic rotation curve (Fich et al. 1989) and with the ambiguity being due to

the near/far degeneracy of kinematic distances.

Corbel & Eikenberry (2003) also present an  $NH_3$  absorption spectrum which uses the radio emission from LBV 1806-20 as the background source, revealing strong absorption from a molecular cloud whose velocity (in both  $NH_3$  absorption and  $CO$  emission) places it at a near distance of 5.7 kpc, setting this as the lower limit to the distance of LBV 1806-20. This observation eliminates the “near” distance as a possibility for LBV 1806-20, leaving only the “far” distance of  $d = 15.1^{+1.8}_{-1.3}$  kpc. As a “sanity check”, Corbel & Eikenberry (2003) go on to show that the observed reddening towards LBV 1806-20 combined with  $CO$  observations of clouds along the line of sight is consistent with the “far” distance and is inconsistent with the “near” distance.

Based on these results, we adopt the distance determination of Corbel & Eikenberry (2003) of  $d = 15.1^{+1.8}_{-1.3}$  kpc. We note that an independent distance estimate for Star B (below) matches this estimate and is also strongly inconsistent with the “near” distance noted above. We discuss this issue further in section 4.1.3.

### 3.4. The Luminosity of LBV 1806-20

Combining the above measurements, we then arrive at luminosity estimates for LBV 1806-20. Taking its brightness of  $K = 8.89 \pm 0.06$  mag and applying an extinction correction of  $A_K = 3.2 \pm 0.2$  mag (corresponding to  $A_V = 29 \pm 2$  mag and  $A_K = 0.112A_V$  (Rieke & Lebofsky 1985)) and a distance modulus of  $15.9 \pm 0.2$  mag (from  $d = 15.1^{+1.8}_{-1.3}$  kpc), we arrive at an absolute K magnitude of  $M_K = -10.2 \pm 0.3$  mag. The absolute visual magnitude and bolometric luminosity of LBV 1806-20 from this number are functions of the star’s spectral class, and also may be affected by free-free contributions to the K-band emission of LBV 1806-20. As discussed below, we do not believe that this contribution is large for LBV 1806-20 (it is  $< 0.1$  mag for the Pistol Star as well), and we include it as an additional 0.1 mag uncertainty in the lower bound for the absolute K-band magnitude, which we now adopt to be  $M_K = -10.2^{+0.4}_{-0.3}$  mag. For a spectral class of O9, the upper end of the range, we have  $V - K = -0.8$  mag to give an absolute visual magnitude of  $M_V = -11.0^{+0.4}_{-0.3}$  mag. The bolometric correction is  $BC = -3.2 \pm 0.2$  mag, giving a bolometric magnitude of  $M_{bol} = -14.2^{+0.5}_{-0.4}$  mag, or a luminosity of  $\sim 4 \times 10^7 L_\odot$ . At the low end of the temperature range (B2 spectral type), the corresponding values are  $M_V = -10.6^{+0.4}_{-0.3}$  mag,  $M_{bol} = -12.0^{+0.5}_{-0.4}$  mag, or a luminosity of  $\sim 5 \times 10^6 L_\odot$ . We have plotted these temperature/luminosity values in Figure 8, along with the corresponding locations of other known extremely luminous stars. Note that even for the lower end of the possible temperature range for LBV 1806-20, it has a luminosity equal to or greater than that of the famous LBV

Eta Carina (Hillier et al. 2001) and the Pistol Star (Figer et al. 1998). Thus, it seems that LBV 1806-20 may (marginally) be the most luminous star currently known.

### 3.5. The Absolute Magnitude and Distance of Star B

Given the photometry, distance estimate, and reddening above, we can also arrive at an absolute magnitude for Star B. If we assume that the reddening toward star B is identical to that for LBV 1806-20 and a distance of 15.1 kpc, the absolute K-band magnitude for this star is  $M_K = -8.6 \pm 0.3$  mag. Note that this is in excellent agreement with the range of absolute magnitudes for WC9 stars in the Galactic Center ( $M_K = -8$  to  $-11$  mag – Blum et al. (2003)). Furthermore, the observed  $H - K$  colors of star B are consistent with the assumed reddening if the intrinsic colors are  $H - K \sim 1.1$  mag, also in excellent agreement with the observed range of intrinsic colors of other WC9 stars ( $H - K = 0.9$  to  $1.6$  mag (Blum et al. 1996))<sup>3</sup>. Thus, the spectral classification and photometry of star B confirm the distance and reddening estimates used for the luminosity of LBV 1806-20 above.

Taking a slightly different approach, we can use the observed range of intrinsic colors and absolute magnitudes for WC9 stars to constrain the distance to star B and provide a completely independent cross-check on the distance to the cluster of stars including LBV 1806-20. The intrinsic color range of Blum et al. (1996) combined with the observed  $H - K = 2.96 \pm 0.08$  mag and the Rieke-Lebofsky reddening law gives a range of  $3.6 > A_K > 2.8$  mag. Combining this with the observed range of  $M_K$  (Blum et al. 2003) for Galactic Center WC9 stars and the observed  $m_K = 10.50 \pm 0.06$  mag gives a range for the distance modulus to star B of  $m_d = 14.9$  mag (low-luminosity, intrinsically-blue, high-reddening) to  $18.7$  mag (high-luminosity, intrinsically-red, low-reddening). Thus, a lower limit on the distance of star B is  $d > 9.5$  kpc, assuming it is no fainter than the intrinsically-faintest known WC9 star in the Galactic Center (an assumption confirmed by the recent discovery of another, even fainter WC9 star in this same cluster (LaVine et al. 2004)). Note that at an alternate assumed distance of  $\sim 4$  kpc (consistent with the G10.2-0.3 cluster of Blum et al. (2001)), star B would be 6 times less luminous than any other known WC9 star, which seems very unlikely (especially given the even fainter WC9 of LaVine et al. (2004)). Thus, this provides yet another independent confirmation that these stars lie in the “far” component of W31 at

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<sup>3</sup>We note that there is not always a one-to-one mapping between infrared and optical spectral classifications of W-R stars, which might suggest some uncertainty here. However, we are using an infrared spectral classification of Star B to compare its infrared properties to other infrared-classified WC9 stars here. Therefore, we conclude that this comparison should be relatively free from any confusion due to differing optical/infrared classifications.

$d = 15.1_{-1.3}^{+1.8}$  kpc, as opposed to the “near” component observed by Blum et al. (2001).

### 3.6. The Luminosities of Stars C & D

The same analyses applied to LBV 1806-20 can also provide luminosity estimates for stars C and D. Based on their strong HeI  $2.112\mu\text{m}$  absorption lines, both of these stars have spectral classes in the range from B0 to B3 (Hanson et al. 1996). Following the analyses for LBV 1806-20 (above), at the distance of 15.1 kpc, for a B1 spectral class, they would have bolometric luminosities of  $\sim 1.6 \times 10^6 L_{\odot}$  and  $1.4 \times 10^6 L_{\odot}$ , respectively. These luminosities are too high for “normal” supergiant stars of this spectral type. However, these luminosities are similar to those observed in early-B hypergiants (luminosity class Ia+) (de Jager 1998) (see Figure 8). Furthermore, hypergiants are distinguished from “normal” supergiants by the presence of broad absorption lines indicative of mass-loss through a wind – much as we see in the  $> 200\text{km s}^{-1}$  linewidths of the Brackett and HeI absorption features in Stars C and D (though, as noted above, line blending may have a non-negligible effect for these lines at this resolution). Therefore, the luminosity and spectral features of Star C and D appear to support their identification as class Ia+ blue supergiants at the same distance and reddening as LBV 1806-20.

Furthermore, if we take the same reddening and distance used for LBV 1806-20, we derive absolute magnitudes of  $M_K = -8.3 \pm 0.3$  mag and  $M_K = -8.0 \pm 0.3$  mag, respectively for stars C and D, without reference to (potentially uncertain) bolometric correction. We note that there are several luminous stars in the Galactic Center with similar effective temperatures (i.e. stars IRS 16SW and IRS 16NE – Najarro et al. (1997)) and absolute magnitudes of  $M_K = -7.5$  to  $-8.0$  mag, in excellent agreement with stars C and D. While the IRS 16 stars are emission-line objects, and stars C and D are absorption line objects, we can at least see that the absolute magnitudes of the brightest B-type stars in this cluster are consistent with the brightest B-type stars in the Galactic Center. This supports at least the *consistency* of the distance and reddening estimates used for LBV 1806-20. Finally, we note that in a cluster such as this, it seems quite likely that some of the brightest stars are in fact binaries, given the large fraction of binarity in high-mass stars. Thus, by selecting the brightest stars in this cluster for spectroscopy, we may be biasing ourselves towards binary stars with apparent luminosity excess (see below for a more detailed discussion of multiplicity in LBV 1806-20).

## 4. Discussion

### 4.1. Caveats to the Luminosity Estimate for LBV 1806-20

#### 4.1.1. Near-infrared excess

One issue for the above luminosity estimate is that LBV 1806-20 might exhibit a near-infrared excess of continuum emission due to warm circumstellar dust (as Star B), free-free emission in the LBV wind, or other processes. Such an IR excess would interfere with our luminosity estimate in several ways. First, it would artificially enhance the K-band brightness of the star, and thus directly cause us to over-estimate the luminosity of LBV 1806-20. Second, it would artificially decrease the apparent equivalent width of the HeI  $2.112\mu\text{m}$  absorption feature, causing us to mis-estimate the star’s temperature and thus its bolometric correction. Finally, it would redden the colors and spectral continuum shape of candidate LBV 1806-20, causing us to over-estimate the reddening correction for the star. Thus, we see that the hypothetical presence of such an excess could significantly alter our luminosity estimate.

However, careful inspection of the observational results gives no evidence for such an excess, and provides several indications against its existence. First of all, as we noted above and as can be seen in Figure 1, there are several stars near LBV 1806-20 with very similar *JHK* colors. If LBV 1806-20 has a significant near-IR excess, then we must also postulate that the majority of the bright stars in/near the cluster also have significant (and virtually identical!) excesses. This is extremely unlikely, if not positively unphysical. Second, the spectral continuum shape in *both* the H and K bands is consistent with a reddened Rayleigh-Jeans distribution for LBV 1806-20 (as well as Stars C and D). On the other hand, the spectral continuum shape in Star B clearly reveals its near-IR excess (likely due to warm dust). Therefore, for an excess to be present in LBV 1806-20, it must extend smoothly over at least the entire H and K bands, thereby significantly altering the observed colors of the star. This conflicts with the observed color match with other cluster stars noted above.

We also note that the LBV stars which most closely resemble LBV 1806-20 in their emission line spectra – AG Car and the Pistol Star – do not show large free-free emission contributions in this wavelength range. The free-free contribution of the Pistol Star in the K-band is negligible for models of the spectral energy distribution (Figer et al. 1998) and estimated to be  $< 0.1$  mag (D. Figer, private communication), while in AG Car the inferred K-band contribution is  $\sim 0.2$  mag (McGregor et al. 1988). While AG Car *does* exhibit mid-IR excess emission, it does not contribute significantly at wavelengths  $\lesssim 10\mu\text{m}$ .

Finally, we note that the supposed dilution of the HeI absorption feature by a large

(e.g.  $> 50\%$ ) near-IR excess would imply an intrinsic equivalent width  $> 4\text{\AA}$  (for an IR excess equal to the blackbody continuum in K-band). However, the temperature range we infer for LBV 1806-20 is near the maximum strength of this line. In fact, *none* of the stars in the census of Hanson et al. (1996) have equivalent widths  $> 3\text{\AA}$ . Thus, the presence of significant dilution of this line by an IR excess would make its spectrum inconsistent with any known type of star.

For all of these reasons, we conclude that LBV 1806-20 does not exhibit any *significant* near-IR excess emission over that expected for a reddened blackbody. By “not significant”, we mean here that the contribution of any IR excess is not large compared to the other uncertainties in our measurement of the star’s luminosity ( $\sim 0.4$  mag). However, as noted in Section 3.4, we have added an additional 0.1 mag of uncertainty to the lower bound for LBV 1806-20, based on a possible expectation of this level of free-free emission as observed in the similar Pistol Star.

#### 4.1.2. Temperature

The issue of the precise temperature for LBV 1806-20 is a difficult one. At a crude level, the spectral continuum shape in H and K bands gives us a firm lower limit of  $\sim 12000K$ , below which we would see spectral curvature away from a Rayleigh-Jeans law, contrary to the observations. However, our primary indicator for the temperature of the star is its HeI  $2.112\mu\text{m}$  absorption feature. The simple presence of this line also indicates an effective temperature greater than  $12000K$  (Hanson et al. 1996). Assuming the relation found between temperature and equivalent width for supergiant stars gives the temperature range from  $18000K$  to  $32000K$ , as noted above. The case of the Pistol Star seems to confirm that this relationship extends to some candidate LBV stars also (Figer et al. 1998).

The variability of this line in LBV 1806-20 unfortunately complicates the matter. As noted above, a change in the stellar temperature to either greater or smaller values, could produce the observed reduction in equivalent width. It has been argued (Humphreys & Davidson 1996) that LBVs have essentially constant bolometric luminosities, and that their apparent brightness variations are due to anti-correlated radius/temperature variations induced by their near-Eddington radiative instability. Thus, a star can experience an increase in temperature with a simultaneous decrease in radius, keeping the bolometric luminosity constant but significantly altering its apparent brightness at wavelengths near the peak of the blackbody spectrum. The observed decrease in the HeI line from LBV 1806-20 could represent such a temperature/radius change. The timescale of this change – several years – is in keeping with the observed timescales for similar changes in other candidate LBV stars.

Assuming constant bolometric luminosity with an increase in temperature, observations in the Rayleigh-Jeans tail of the emission spectrum should follow a dependence  $F_\nu \propto T^{-3}$ . Thus, the possible drop by  $\sim 0.5$  mag between the observations of Kulkarni et al. (1995) and our observations here could indicate a temperature increase in LBV 1806-20 by  $\sim 10\%$ , with a corresponding decrease in HeI equivalent width. Also note that if the HeI decrement were due to a temperature *decrease* to  $12000 - 14000K$  (and corresponding radius *increase*), we would expect an apparent K-band *brightening* in LBV 1806-20 by  $\sim 1.0$  mag, which is ruled out by the observations.

In any case, we note that our temperature estimate is based on the higher equivalent width of HeI (lower temperature), and thus provides us with a lower estimate on the bolometric luminosity. Furthermore, the temperature changes hinted at by the HeI variability and possible associated photometric variability described above are well within the range of our stated uncertainties in temperature. Finally, we note that a more precise determination of the temperature (and thus luminosity) of LBV 1806-20 may be possible in the future, using detailed models for the stellar spectrum as developed by Figer et al. (1998) for the Pistol Star.

#### 4.1.3. Distance

As noted above, the distance to this cluster is the primary subject of Corbel et al. (1997) and Corbel & Eikenberry (2003), and those papers provide detailed discussion. However, two new points are worth emphasizing here. First of all, the radial velocity of LBV 1806-20 confirms its association with the molecular clouds at  $\sim 4$  kpc or  $15.1^{+1.8}_{-1.3}$  kpc. It is important to note that intermediate distances are essentially ruled out, as they would require peculiar velocities of LBV 1806-20 as large as  $> 100 \text{ km s}^{-1}$ , which is much larger than the typical velocity dispersions for such massive stars. Secondly, the spectral types for stars B, C, and D are all consistent with their absolute K-band magnitudes if they (and thus LBV 1806-20) are all located at the distance of  $15.1^{+1.8}_{-1.3}$  kpc given by Corbel & Eikenberry (2003). Furthermore, the observed magnitude of star B combined with the known range of absolute magnitudes for WC9 stars strongly rules out the “near” distance for this cluster of stars, and independently sets a minimum distance of at least 9.5 kpc. Thus, these stars provide independent confirmation of the original distance arguments of Corbel et al. (1997) and Corbel & Eikenberry (2003), resulting in a total of three independent lines of evidence (kinematic distance plus  $NH_3$  absorption, absolute magnitude range of Star B, IR extinction) that show LBV 1806-20 lies at the “far” distance of  $15.1^{+1.8}_{-1.3}$ .

For the sake of completeness, we also consider the luminosity of Star A using distance



estimates that exclude the kinematic distance measurement discussed above and in Corbel & Eikenberry (2003). That leaves two major distance indicators – the ammonia absorption feature, which places LBV 1806-20 at a distance of at least  $> 5.5$  kpc, and the absolute K-band magnitude of Star B, which places the cluster at  $d > 9.5$  kpc. Note that these two indicators are consistent with each other, as they are lower limits, and both confirm that LBV 1806-20 does not lie at the “near” kinematic distance of  $\sim 4$  kpc. Taking  $d = 9.5$  kpc as a lower limit on the distance to the cluster, we can place lower limits on the luminosity of LBV 1806-20. For a temperature at the minimum of our range above, we have for the lower limit  $L_{bol} > 2 \times 10^6 L_{\odot}$ . At the upper end of our temperature range above, the lower limit becomes  $L_{bol} > 1.6 \times 10^7 L_{\odot}$ . We note again that these estimates ignore the kinematic information on LBV 1806-20, which places it at  $\sim 15$  kpc. If LBV 1806-20 were in fact to lie at  $\sim 10$  kpc, it would have a velocity deviation of several tens of kilometers per second from the Galactic rotation curve. We also note that LaVine et al. (2004) have identified another WC9 star in this cluster which is  $\sim 1$  mag fainter than Star B, which would increase the “non-kinematic” distance lower limit to  $\sim 12.5$  kpc, which is close to the lower end of the confidence interval for the kinematic distance estimate of Corbel & Eikenberry (2003).

We also note here that there is strong reason to believe that all of these stars (the candidate LBV, Stars B, C, D, and the soft gamma repeater SGR 1806-20) are in fact members of the same cluster. The great rarity of LBV candidates and SGRs in the Galaxy make a chance association of two so close together very small ( $< 10^{-5}$  probability (Kulkarni et al. 1995)). This probability is decreased even further by the fact that the measured IR extinction towards the LBV candidate matches the X-ray absorption towards the SGR (Eikenberry et al. 2001). The additional discovery of a very rare WC9d star (Star B) and two OB stars (C and D), all with identical reddening, seems to further show strong evidence for the existence of a physical association of these massive stars and their remnants. Additional support comes from the mid-infrared observations of Fuchs et al. (1999), which shows that all of these stars lie within an extended envelope of mid-IR emission, presumably due to hot dust in their natal molecular cloud. The work of LaVine et al. (2004) reveals an additional 2 Wolf-Rayet stars (one WC9 and one WN5), as well as multiple other OB stars in this region increases the over-density of massive stars here, which would seem to cement the conclusion that this is in fact a physical association of massive stars at the same distance. In fact, the surface density of very massive stars here is within a factor of a few of the most dense concentrations seen in our Galaxy, such as the Arches cluster (Figer et al. 2002).

Finally, if we exclude both the kinematic arguments above *and* the absolute magnitude of Star B, the ammonia absorption feature places another lower limit on the distance to the candidate LBV 1806-20 of  $> 5.7$  kpc (Corbel & Eikenberry 2003). This results in a luminosity lower limit of  $> 7 \times 10^5 L_{\odot}$ . Note again that this distance is problematic when considering

the measured velocity of the molecular cloud and the candidate LBV, requiring them to have peculiar velocities of  $\sim 100 \text{ km s}^{-1}$  compared to the expected Galactic rotation curve at this location – an extreme deviation considering that such massive stars are generally a “cold” population in kinematic terms. Furthermore, at this distance, Star B would be approximately 4 times less luminous than any WC9 star seen in the Galactic Center (and the WC9 of LaVine et al. (2004) would be  $\sim 12$  times less luminous than any of the Galactic Center WC9 stars). Thus, this distance seems incompatible with several observational facts. Nevertheless, we include this distance estimate here for completeness.

#### 4.1.4. *Is it a cluster or multiple system?*

Perhaps the strongest caveat to (at least the lower limit for) the luminosity of LBV 1806-20 is the issue of the star’s possible multiplicity. A proposed explanation for the observed luminosities of objects such as the Pistol Star and LBV 1806-20 is that they are in fact unresolved *clusters* of luminous stars. However, our speckle observations contradict this conclusion in the case of LBV 1806-20. For a distance of 15.1 kpc, the upper limit of 60-mas on any extension corresponds to 0.0044 pc or  $\sim 900 \text{ AU}$  FWHM. This is more than an order of magnitude smaller than any known cluster. Thus, it is very unlikely that LBV 1806-20 is an unresolved cluster of stars.

On the other hand, OB stars in open clusters are often ( $> 50\%$  fraction) in binaries, implying that LBV 1806-20 may also be a binary system. Our current observations do not strictly rule out a close binary (or even triple system) as an explanation for LBV 1806-20. For a circular orbit with a  $\sim 450 \text{ AU}$  semi-major axis and a total binary mass of  $\sim 200 M_{\odot}$  (see below), even seen edge-on, we derive differential orbital velocities for similar-mass components of  $\sim 5 - 10 \text{ km s}^{-1}$  – well below the observed line widths. Thus, it seems quite possible that LBV 1806-20 is a binary/multiple system. However, we note that even at our lower luminosity range, for equal components, each star would be approximately as luminous as  $\eta \text{ Car}$ . For mass ratios different from one, the more massive component would increase in luminosity from this level. So, even if LBV 1806-20 is in fact a binary/multiple system, we are still left with extremely luminous (and massive) stars composing the system.

Finally, the observed emission line variability and depth of the HeI  $2.112\mu\text{m}$  feature also present some possible evidence against multiplicity in LBV 1806-20. The emission lines vary by factors of several, as shown above, implying that one object is probably the dominant source of radiation in the system. On the other hand, in an ultra-luminous binary (such as LBV 1806-20 would have to be), wind-wind collisions may be a significant source of line emission, and thus explain the large-amplitude variability in this context. The observed

depth of the HeI absorption line is less easy to explain away. The depth of this line is such that either one component has a weaker feature and the other star has the deepest such absorption feature known (to compensate), or both stars have nearly-equally deep absorption features. While this latter seems somewhat unlikely, it is still possible. Therefore, we conclude that the issue of multiplicity in LBV 1806-20 remains an open question.

## 4.2. The Mass of LBV 1806-20

If we assume that LBV 1806-20 is in fact a single star, its luminosity provides a current mass estimate, assuming that the star radiates at its Eddington luminosity where radiation pressure at the surface matches the star’s gravity. At the lower end of the luminosity range for the best distance estimate ( $d = 15.1^{+1.8}_{-1.3}$  kpc), we derive a minimum present-day mass of  $M > 133 M_{\odot}$ , assuming  $N(H)/N(He) = 10$  (Hillier et al. 2001). Furthermore, the Eddington limit is a lower limit to the mass – realistic models of massive stars typically have  $L \sim 0.6 - 0.7 L_{Edd}$  (i.e. Hillier et al. (2001); Figer et al. (1998)). Thus a realistic lower limit on the mass of LBV 1806-20 in the same context as similar estimates for other massive stars is  $M > 190 M_{\odot}$ . (For completeness, at the alternative distance lower limits, this mass limit becomes  $M > 76 M_{\odot}$  ( $d > 9.5$  kpc, ignoring kinematic measurements) and  $M > 27 M_{\odot}$  ( $d > 5.5$  kpc, ignoring the absolute magnitudes of the WC9 stars)). The following discussion assumes the mass to be  $> 190 M_{\odot}$ .

On the other hand, LBV 1806-20 may be a relatively tight binary, with a projected semi-major axis  $< 450$  AU (based on our speckle imaging above). If so, then the most even distribution of luminosity (which deviates most from the single star arguments above) has each star at  $> 2.5 \times 10^6 L_{\odot}$ . Following the same arguments above based on Eddington luminosities, then each binary component has a present-day mass  $> 90 M_{\odot}$ . It is not currently clear whether this scenario is physically plausible. For instance, if during formation one of the stars ignited slightly before the other, the radiation pressure from such a luminous object so nearby might photoevaporate the second binary component. (However, as argued below, shock-induced star formation may invalidate this argument to some extent). In any case, our reliance on the Eddington luminosity for mass estimation indicates that for  $L > 5 \times 10^6 L_{\odot}$ , the total system mass should be  $> 190 M_{\odot}$ .

### 4.3. Comparison to the Pistol Star

The star that most closely resembles LBV 1806-20 in spectral characteristics (see discussion above) and luminosity is the Pistol Star (Figer et al. 1998). This is particularly important in that segments of the astronomical community have been slow to accept the luminosity estimates for the Pistol Star, and various appeals to exceptional circumstances in the Pistol Star’s unique properties and location (very close to the Galactic Center) are often made. However, the close match in spectral characteristics and luminosity between these two stars demonstrates that the Pistol Star is not unique in its properties. Furthermore, LBV 1806-20 is located at a Galactocentric radius of  $\sim 7$  kpc – nearly out to the Solar Circle, and certainly very far removed from the Galactic Center itself. This shows conclusively that the formation of very massive stars is an ongoing process in our Galaxy in the current epoch, and furthermore that this process is not limited to the extreme environment of the Galactic Center.

We also note that the similarity between the spectra of LBV 1806-20 and the Pistol Star may indicate that LBV 1806-20 lies at the lower end of the allowed luminosity range in Figure 8. However, verification of this possibility requires higher resolution spectra and detailed modeling of the stellar atmosphere, which should be carried out as future work.

### 4.4. The Ultimate Fate of LBV 1806-20

Due in large part to the apparent connection between supernovae and  $\gamma$ -ray bursts (i.e. Price et al. (2003); Hjorth et al. (2003)), there has been considerable progress in recent years concerning the end-state evolution of very massive stars. Heger et al. (2003) present final evolutionary scenarios for a wide range of stellar masses and metallicity. If we assume that LBV 1806-20 had an initial mass of  $\sim 200 M_{\odot}$  and has near-solar metallicity, Heger et al. (2003) show that the star will end its days as a SNIb/c explosion producing a neutron star. This result is contrary to the previous “standard” assumption that all very massive stars produce black holes (or disintegrate in pair-instability supernovae), and depends on heavy mass-loss due to tremendous stellar winds to strip the stellar core bare and diminish the final core mass. Note that Gaensler et al. (2001) infer the presence of just such a strong wind from LBV 1806-20 from the radio emission of G10.0-0.3.

This result could also extend to the progenitor of SGR 1806-20 – if it was only slightly more massive than LBV 1806-20 it could in fact evolve more rapidly, explode, and yet leave behind a neutron star remnant. The fact that SGR 1806-20 is not an ordinary neutron star, but also a SGR and magnetar (Kouveliotou et al. 1998), and that other SGRs seem to be

associated with massive star clusters (Vrba et al. 2000) may indicate that the final evolution of some very massive stars not only produces neutron stars, but in fact tends to produce *highly-magnetized* neutron stars.

#### 4.5. The Origin of LBV 1806-20 and the Cluster

Previously, theorists have argued that stars (and implicitly tight binaries) greater than  $\sim 100M_{\odot}$  should be impossible to form under normal circumstances at solar metallicity, due to radiation pressure on dust grains in the star-forming material, radiative heating of the accreting gas, and formation of HII regions before the complete accretion of the envelope (Bond et al. 1984). These calculations assume spherical symmetry, and the likely deviations from this symmetry (e.g. an accretion disk) will raise the upper limit on stellar masses. However, most currently published models of stellar evolution stop at  $\sim 100 - 120M_{\odot}$  (i.e. Leitherer et al. (1999); Schaerer et al. (1993)), at least implicitly accepting this as an upper limit to stellar masses. Thus, it would seem that the existence of LBV 1806-20 and of other massive stars (the Pistol Star, R136a1, R136a2) may require some revision in our understanding of very massive star formation, particularly if they are near solar metallicity. Alternately, pressure-induced star formation due to expanding HII regions or supernova shocks presents another possible exception to the upper limit above.

This possibility is particularly intriguing given the environment of LBV 1806-20 – the cluster contains both a late-type Wolf-Rayet star (Star B) as well as at least one neutron star (SGR 1806-20 – see Eikenberry et al. (2001)). Since both of these objects are thought to be more evolved than the candidate LBV (Massey (2003); Conti (1976)) and stellar evolution progresses more rapidly for more massive stars, we are left to conclude either that their progenitors were even more massive than LBV 1806-20 (which seems unlikely though not necessarily impossible – see below), or that star formation in this location did not occur at single epoch, but has been spread over time. SGR 1806-20 alone implies that at least one supernova event must have occurred previously in this region (though it is not at all certain that this particular event occurred *before* the formation of the candidate LBV star). As a consequence, it seems quite possible that the formation of LBV 1806-20 was triggered by the expanding HII regions or supernova events from prior epochs of star formation at this location, resulting in its unusually high mass. We also note the simultaneous presence of candidate LBV and WR stars in the Quintuplet cluster (Figer et al. 1998), as well – confirming that this situation is not unique and revealing yet another similarity between LBV 1806-20 and the Pistol Star.

## 5. Conclusions

We have presented near-infrared imaging and spectroscopy of the luminous star LBV 1806-20 and 3 other nearby luminous stars. Based on the results we conclude that LBV 1806-20 has spectral characteristics very similar to those of AG Car, the Pistol Star, and P Cyg – all luminous blue variables – and is thus likely to be an LBV itself. The nearby luminous stars B, C, and D are Wolf-Rayet WC9d and possible blue hypergiant stars forming part of a cluster which includes LBV 1806-20. Their absolute magnitudes and bolometric luminosities are consistent with other known stars with similar spectral types, confirming the distance and reddening estimates for LBV 1806-20 ( $15.1_{-1.3}^{+1.8}$  kpc and  $A_V = 29 \pm 2$  mag). With a surface temperature in the range 18000-32000K, LBV 1806-20 has a bolometric luminosity  $> 5 \times 10^6 L_\odot$ . If we drop kinematic measurements of the distance ( $15.1_{-1.3}^{+1.8}$  kpc), we have a lower limit on the distance of  $> 9.5$  kpc, and on the luminosity of  $> 2 \times 10^6 L_\odot$ , based on the cluster stars. If we drop both the kinematic and cluster star indicators for distance, an ammonia absorption feature sets yet another lower limit to the distance of  $> 5.7$  kpc, with a corresponding luminosity estimate of  $> 7 \times 10^5 L_\odot$  for the candidate LBV 1806-20. Our speckle imaging shows conclusively that LBV 1806-20 is *not* an unresolved cluster of stars, though it may be a binary/multiple system. If LBV 1806-20 is a single or multiple star, its total mass exceeds  $190M_\odot$  (at the  $\sim 15$  kpc distance). Finally, the presence of LBV 1806-20 with more evolved stars in the same cluster (i.e. the W-R WCL star and SGR 1806-20) implies that star formation may have occurred over multiple epochs in this region of space.

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## REFERENCES

- Blum,R.D., Ramirez,S.V., Sellgren,K., Olsen, K. 2003, astro-ph preprint 0307291
- Blum,R.D., Daminieli,A., Conti,P.S. 2001, AJ, 121, 3149
- Blum,R.D., Sellgren,K., DePoy, D.L. 1996, ApJ, 470, 864
- Bond,J.R., Arnett,W.D., Carr,B.J. 1984, ApJ, 280, 825
- Cardelli,J.A., Clayton,G.C., Mathis,J.S. 1989, ApJ, 345, 245
- Conti,P. 1976, Mem. Soc. R. Sci. Liege 9, 193
- Corbel,S. & Eikenberry,S.S. 2003, A&A, in press
- Corbel,S. et al., 1997, ApJ, 478, 624
- deJager,C. 1998, Astron. & Astrophys. Rev., 8, 145
- Depoy,D., Atwood,B., Byard,P.L., Frogel,J., O’Brien,T.P. 1993, SPIE, 1946, 667
- Eikenberry,S.S., Garske,M.A., Hu,D., Jackson,M.A., Patel,S.G., Barry,D.J., Colonna,M., Houck,J.R., ApJ, 563, L133
- Fich,M., Blitz,L., Stark,A. 1989, ApJ, 342, 272
- Figer,D.F. et al., 2002, ApJ, 581, 258
- Figer,D.F. et al., 1998, ApJ, 506, 384
- Figer,D.F., McLean,I.S., Najarro, F. 1997, ApJ, 486, 420
- Fuchs,Y., Mirabel,F., Chaty,S., Claret,A., Cesarsky,C.J., Cesarsky,D.A. 1999, A&A, 350, 891
- Gaensler, B.M., Slane, P.O., Gotthelf, E.V., Vasisht, G. 2001, ApJ, 559, 963
- Geballe, T.R., Najarro, F., Figer,D.F., 2000, ApJ, 530, 97
- Hanson,M.M., Conti,P.S., Rieke,M.J. 1996, ApJS, 107, 281
- Heger,A., Fryer,C.L., Woosley,S.E., Langer,N., Hartmann,D.H. 2003, ApJ, 591, 288
- Hillier,J.D., Davidson,K., Ishibashi,K., Gull,T.R. 2001, ApJ, 553, 837
- Hjorth,J. et al., 2003, Nature, 423, 847

- Humphreys, R.M. & Davidson, K. 1996, PASP, 106, 1025
- Houck, J.R. & Colonna, M.R., *in preparation*
- Hurley, K., Kouveliotou, C., Cline, T., Mazets, E., Golenetskii, S., Frederiks, D.D., van Paradijs, J. 1999, ApJ, 523, L37
- Kaaret, P. et al. 2001, MNRAS, 321, L29
- Kaplan, D.L., Fox, D.W., Kulkarni, S.R., Gotthelf, E.V., Vasisht, G., Frail, D.A. 2002, ApJ, 564, 935
- Kouveliotou, C., Dieters, S., Strohmayer, T., van Paradijs, J., Fishman, G. J., Meegan, C. A., Hurley, K., Kommers, J., Smith, I., Frail, D., Murakami, T. 1998, Nature 393, 235
- Kulkarni, S.R. & Frail, D.A. 1993, Nature, 365, 33
- Kulkarni, S.R., Matthews, K., Neugebauer, G., Reid, I.N., van Kerkwijk, M.H., Vasisht, G. 1995, ApJ, 440, L61
- LaVine, J.L., Eikenberry, S.S., Smith, J.D. 2003, *in preparation*
- Leitherer, C. et al. 1999, ApJS, 123, 3
- Macfadyen, A., Woosley, S., Heger, A. 2001, ApJ, 550, 410
- Macfadyen, A.I. & Woosley, S.E. 1999, ApJ, 524, 262
- Massey, P. 2003, astro-ph preprint 0307531
- Massey, P. & Hunter, D.A. 1998, ApJ, 493, 180
- McGregor, P.J., Hyland, A.R., Hillier, D.J. 1988, ApJ, 324, 1071
- Mereghetti, S., Cremonesi, D., Feroci, M., Tavani, M. 2000, *Å*, 361, 240
- Morris, P.W., Eenens, P.R.J., Hanson, M.M., Conti, P.S., Blum, R.D. 1996, ApJ, 470, 597
- Najarro, F., Krabbe, A., Genzel, R., Lutz, D., Kudritzki, R.P., Hillier, D.J. 1997, *Å*, 325, 700
- Ober, W.W., El Eid, M.F., Fricke, K.J. 1983, A&A, 119, 61
- Price, P.A. et al., 2003, Nature, 423, 844
- Rieke, G.H. & Lebofsky, M.J. 1985, ApJ, 288, 618



- Schaerer,D., Meynet,G., Maeder,A., Schaller,G. 1993, A&AS, 98, 523
- Smith, N. 2001, preprint
- van der Hucht, K.A. 2001, *New Astronomy Rev*, 45, 135
- van Kerkwijk,M.H., Kulkarni,S.R., Matthews,K., Neugebauer,G., 1995, ApJ, 444, L33
- Vasisht,G., Frail,D.A., Kulkarni,S.R. 1995, ApJ, 440, L65
- Vrba, F.J., Henden, A.A., Luginbuhl, C.B., Guetter, H.H., Hartmann, D.H., Klose, S. 2000, ApJ, 533 L17

Table 1. Photometry of Stars

Star	J-band ( $1.25\mu\text{m}$ )	H-band ( $1.65\mu\text{m}$ )	K-band ( $2.2\mu\text{m}$ )
LBV 1806-20	13.93 (8) <sup>1</sup>	10.75 (5)	8.89 (6)
B	17.79 (28)	13.46 (5)	10.50 (6)
C	16.38 (8)	12.76 (5)	10.80 (6)
D	16.02 (8)	12.84 (8)	11.11 (9)

<sup>1</sup>Units are magnitudes. Values in parentheses indicate uncertainties in the final listed digit.

Table 2. Spectral Lines in LBV1806-20<sup>1</sup>

Identification	Wavelength (Å)	Centroid (Å)	$W(\text{Å})^2$	$\Delta V (km s^{-1})^3$	Comment
HI (Pa $\beta$ )	12817	12816	-82 (5)	167	
HI (Br 19-4)	15260	15241	-2.0 (9)	...	
FeII & HI (Br 18-4)	15330, 15341	15322	-4.6 (9)	197	Blend
HI (Br 17-4)	15439	15425	-1.1 (6)	...	Broad P-Cygni?
HI (Br 16-4)	15557	15550	-6.9 (5)	...	
HI (Br 15-4)	15701	15691	-6.4 (4)	189	
FeII&NIII&CIII		15750	-7.2 (4)	...	Blend
HI (Br 14-4 )	15880	15880	-7.5 (5)	168	
FeII		15993	-1.7 (3)	115	
HI (Br 13-4)	16109	16110	-5.4 (3)	60	
HI (Br 12-4)	16407	16404	-8.1 (3)	...	Blend
FeII	1.6435	16444	-7.7 (3)	178	
FeII	16768	16768	-6.7 (3)	...	Blend
HI (Br 11-4)	16806	16816	-11.0 (3)	...	Blend
FeII	16873	16874	-8.4 (4)	210	Structure?
HeI	17003	17009	-3.5 (3)	0	P-Cygni?
FeI & FeII (?)		17110	-1.60 (16)	122?	Blend?
HI (Br 10-4)	17362	17365	-11.7 (2)	40?	P-Cygni?
FeII	17414	17415	-3.4 (2)	245?	Blend?
FeII	17449	17456	-1.9 (2)	...	
FeII (?)	20460	20460	-0.7 (3)		
HeI	20581	20581	-17.4 (3)	100	Structure?
FeII	20888	20888	-2.58 (19)	147	Blend?
HeI	21121	21122	0.76 (17)	...	Blend
FeII	21327	21321	-0.97 (12)	...	
MgII	21368	21369	-7.20 (12)	174	
MgII	21432	21429	-3.65 (12)	193	
HI (Br $\gamma$ = Br 7-4)	21655	21655	-44.2 (3)	159	
FeII	21878	21870	-1.14 (11)	...	Blend
NaI	22056	22054	-2.38 (16)	...	
NaI	22083	22091	-0.95 (13)	...	
FeII	22237	22240	-1.22 (10)	...	
FeII	22534	22540	-0.41 (11)	...	

Table 2—Continued

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<sup>1</sup>Columns give the line identification, rest wavelength (in air) , observed line centroid wavelength (in air), equivalent width, and line full-width at half-maximum converted to Doppler velocity.

<sup>2</sup>Equivalent widths, with negative values indicating emission and positive values indicating absorption. Values in parentheses indicate uncertainties in the final listed digit.

<sup>3</sup>ine widths reported result from taking the measured line width and subtracting the instrumental response function in quadrature. The instrumental response was determined from OH sky lines expected to be free from blending.

Fig. 1.— *Three-color near-infrared image of the field of LBV 1806-20, coded with J-band = blue, H-band = green, K-band = red. Labels indicate LBV 1806-20 (A) and the 3 other stars (B,C,D) for which we obtained near-infrared spectra. Blue colors indicate foreground objects, while colors similar to LBV 1806-20 indicate hot stars with similar reddening. Coordinates are J2000.0*

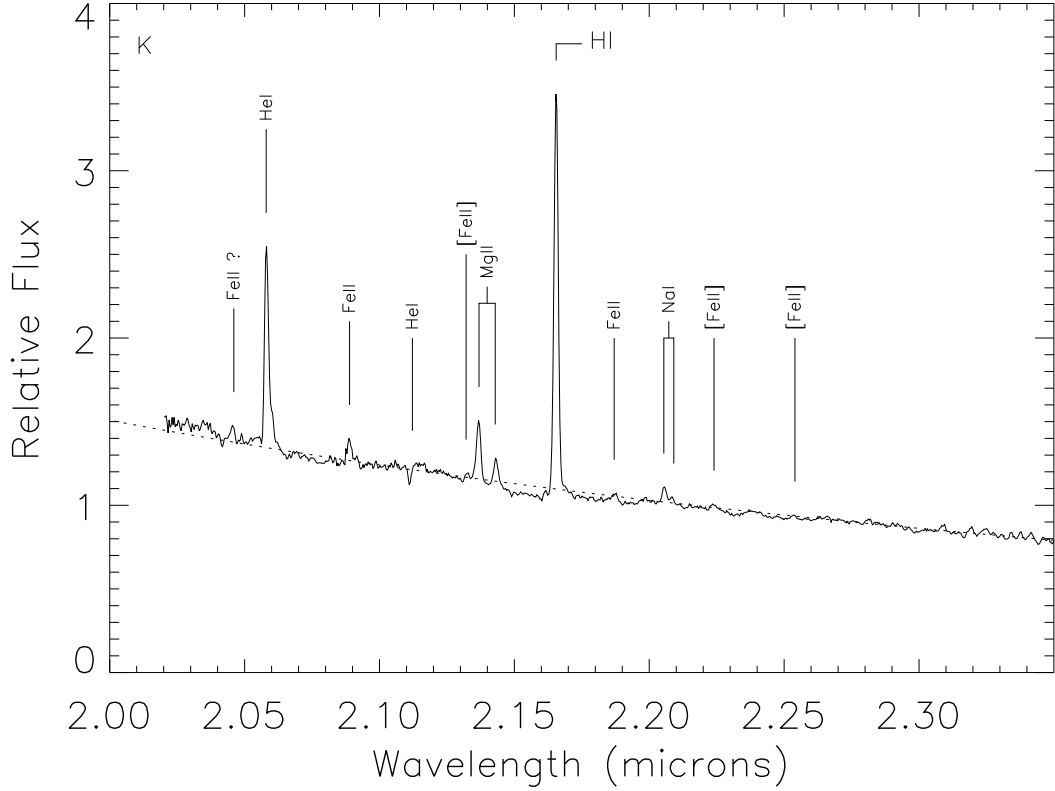


Fig. 2.— *Near-infrared spectrum of LBV 1806-20 in the K band, de-reddened with  $A_V = 29$  mag, following the reddening law of Rieke & Lebofsky (1985). The dotted line indicates the spectral shape of a blackbody with  $T > 12000$  K. The spectrum closely resembles that of the Pistol Star and AG Car, and is typical for LBVs at this wavelength.*

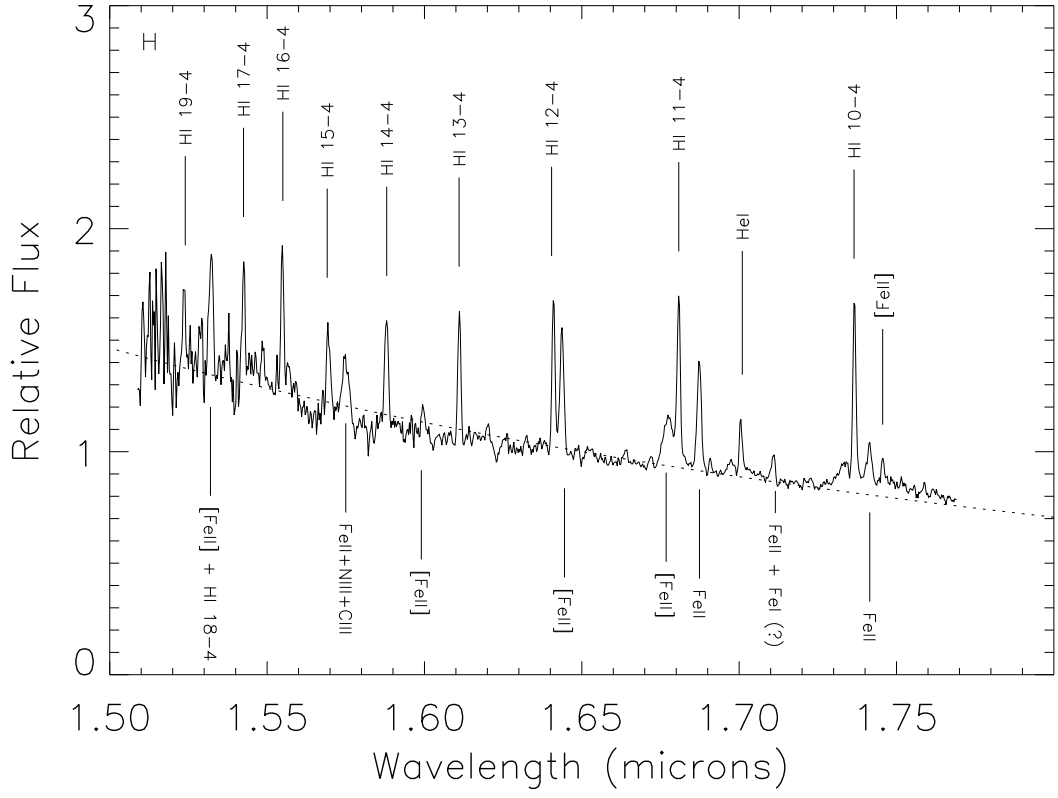


Fig. 3.— Near-infrared spectrum of LBV 1806-20 in the H band, de-reddened with  $A_V = 29$  mag, following the reddening law of Rieke & Lebofsky (1985). The dotted line indicates the spectral shape of a blackbody with  $T > 12000$  K. The emission lines are primarily due to the Brackett series and FeII.

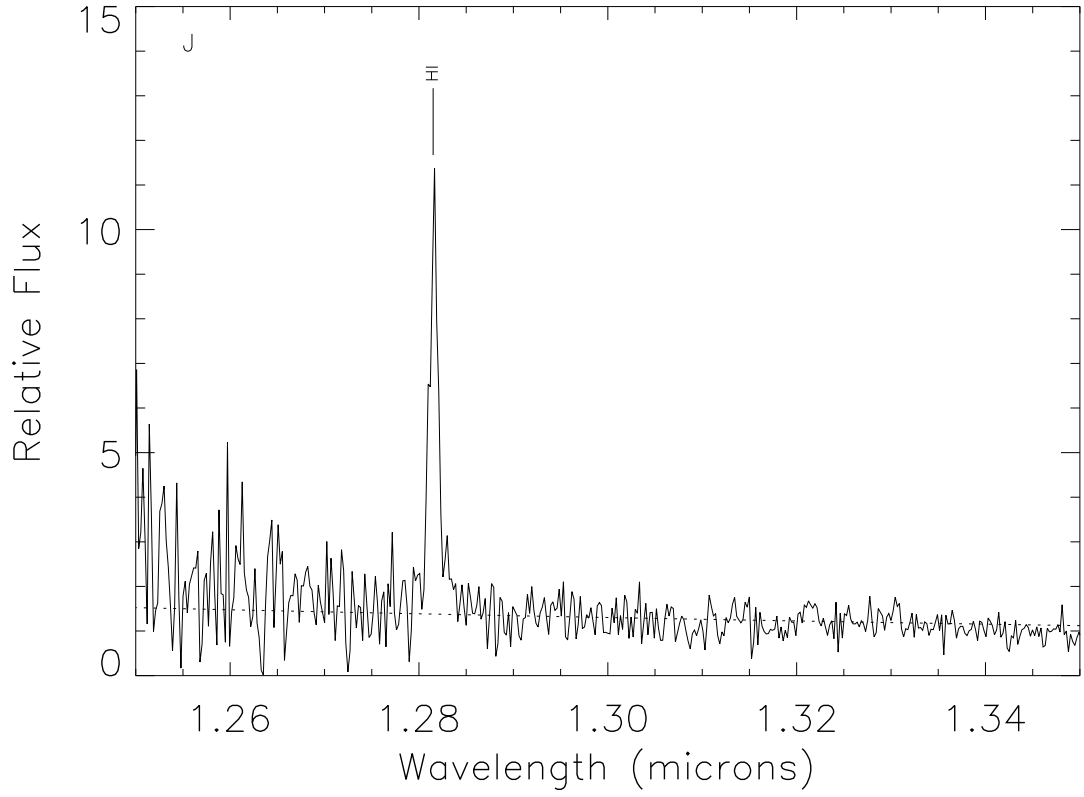


Fig. 4.— *Near-infrared spectrum of LBV 1806-20 in the J band, de-reddened with  $A_V = 29$  mag, following the reddening law of Rieke & Lebofsky (1985). The dotted line indicates the spectral shape of a blackbody with  $T > 12000$  K. The single strong emission line is Pa $\beta$ .*

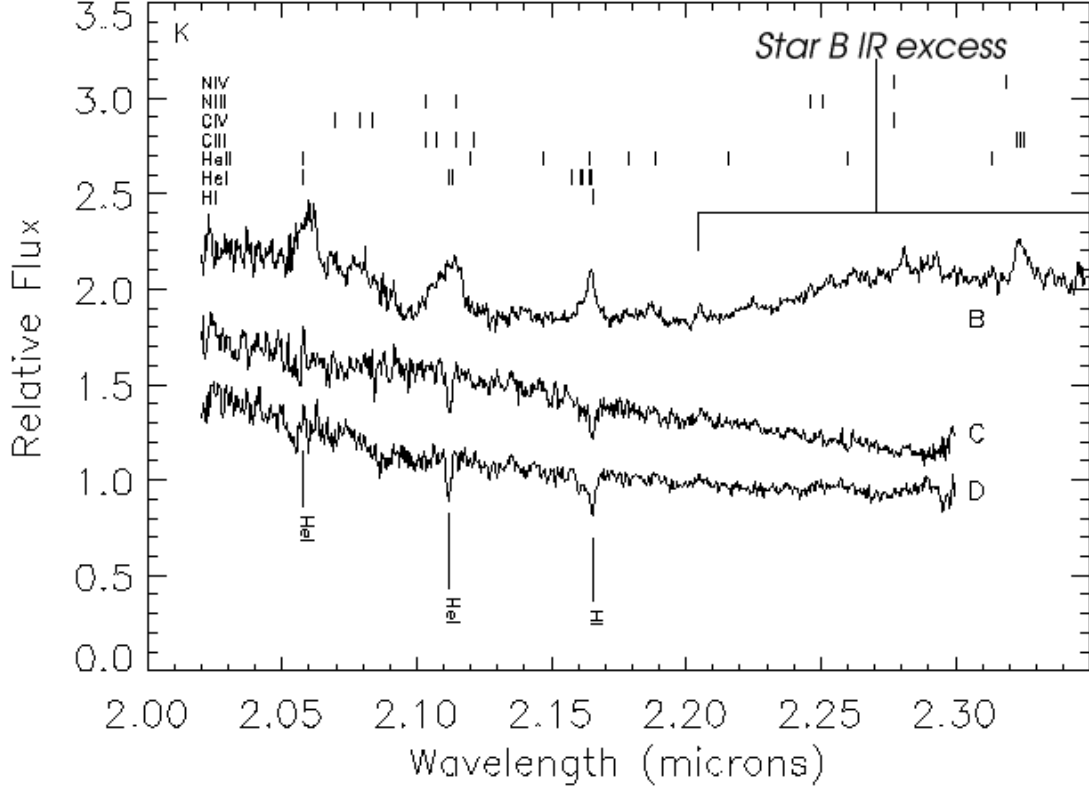


Fig. 5.— Near-infrared spectra of stars B, C, and D in the K band. All spectra have been de-reddened with  $A_V = 29$  mag, following the reddening law of Rieke & Lebofsky (1985), and the spectra of Stars B and C are vertically shifted for clarity. Star B shows a bumpy continuum with a red excess along with broad blended helium, carbon, and nitrogen emission lines typical of dusty late WC-type Wolf-Rayet stars. Stars C and D both show blue continua with HeI 2.112 $\mu$ m and HI (Br $\gamma$ ) in absorption, typical of late O- or early B-type supergiants. Stars C and D also show some indications of HeI 2.058 $\mu$ m in emission/absorption – possibly a self-absorbed P-Cygni profile.



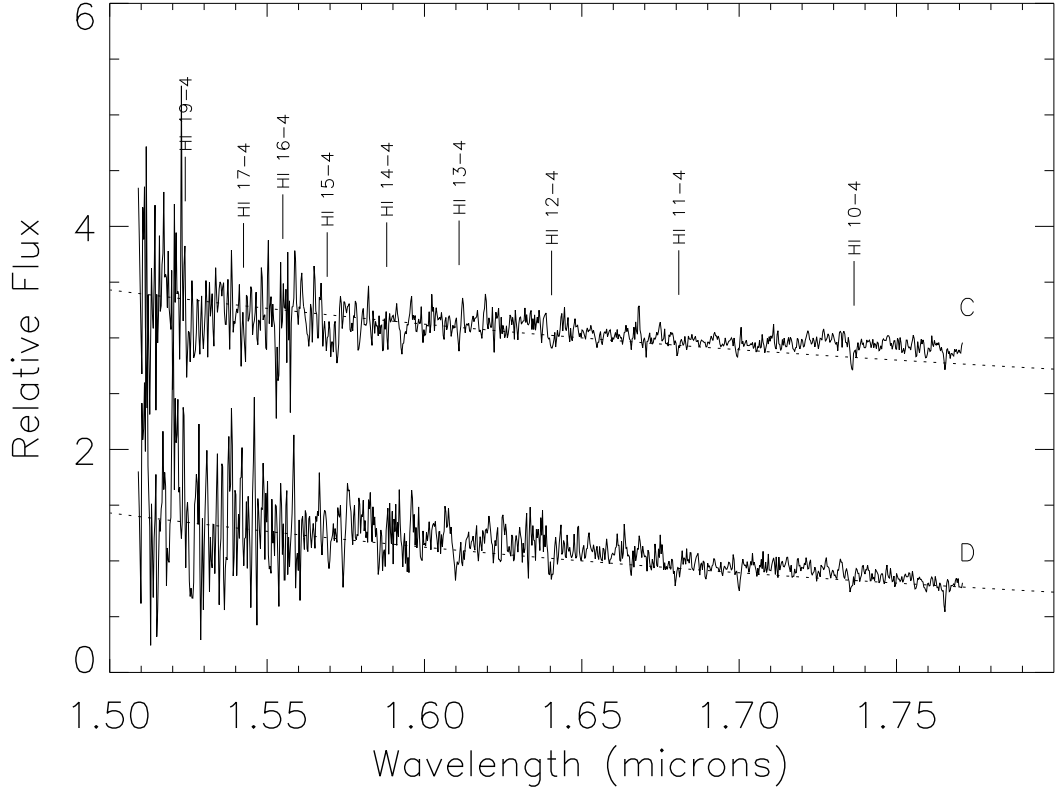


Fig. 6.— Near-infrared spectra of stars *C* and *D* in the *H* band, de-reddened with  $A_V = 29$  mag, following the reddening law of Rieke & Lebofsky (1985). The dotted lines indicates the spectral shape of a blackbody with  $T > 12000$  K. The relatively poor spectral quality is due to a combination of poor observing conditions and the reddening towards these stars.

Fig. 7.— High-resolution speckle images of LBV 1806-20 in the *K* ( $2.2\mu\text{m}$ ) band taken at the Palomar 5-m telescope on June 30, 1999. The top left image is of LBV 1806-20 taken with a  $0.036''$  per pixel scale ( $4.6''$  field of view) and a stretch from 0 (sky background) to the maximum of the image. This image has a FWHM of  $0.130''$ , near the telescope diffraction limit of  $0.110''$ . The top right image is the difference between the image of LBV 1806-20 and 2 PSF reference stars, with a stretch from 0 (sky background) to 15 times the RMS noise level ( $\sim 0.005$  times the peak in the top left image). The bottom image shows the residuals to a simulated cluster with a Gaussian profile of FWHM =  $0.0039$  pc, with the same stretch as the top right image. Note that residuals for such a cluster significantly exceed the actual observed residuals, indicating that LBV 1806-20 is not a cluster of stars.

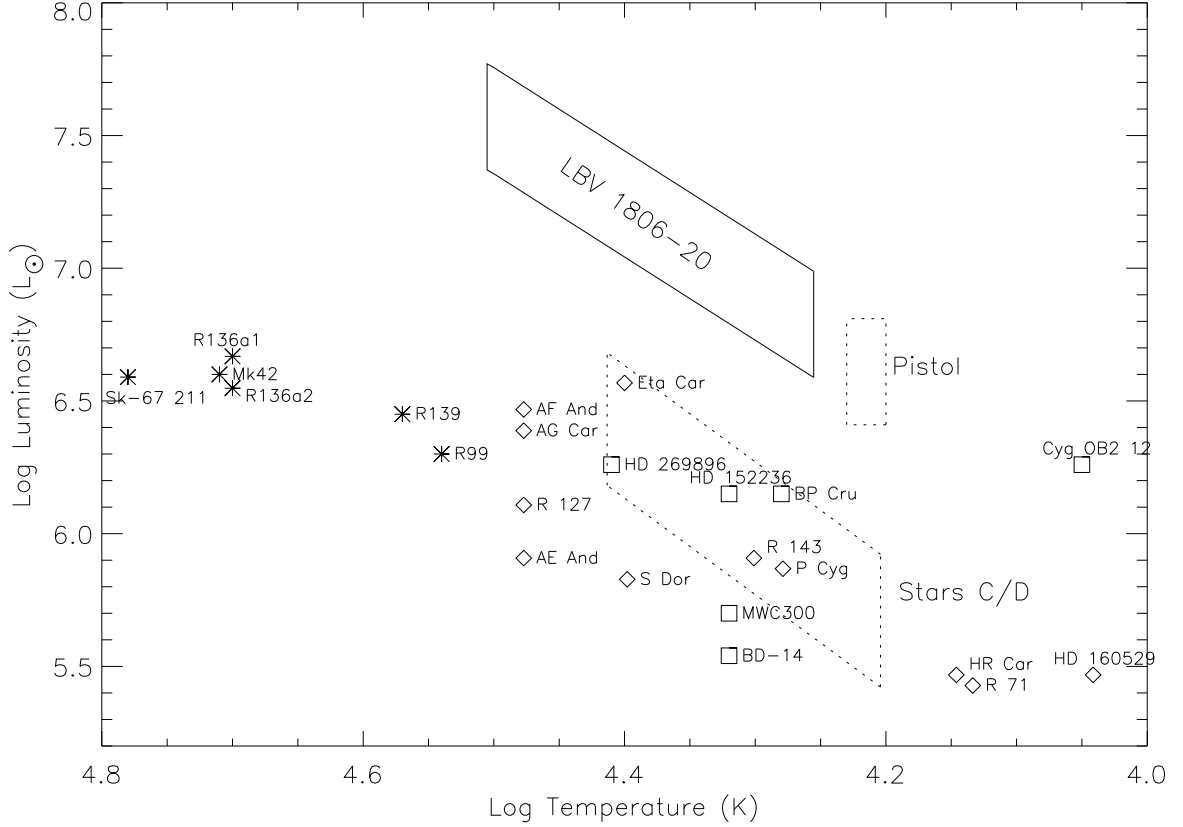


Fig. 8.— *Hertzsprung-Russell diagram including LBV 1806-20 and other hot luminous stars. Diamonds indicate candidate LBV stars, squares indicate Ia+ hypergiants, asterisks indicate O-type supergiants, and regions indicate the locations of LBV 1806-20, Stars C and D, and the Pistol Star. Uncertainties in the temperatures of LBV 1806-20 and Stars C and D dominate the uncertainty in their luminosities. Note that even at the lowest temperature, the luminosity of LBV 1806-20 exceeds that of the famous LBV Eta Car and overlaps the upper end of the Pistol Star’s luminosity range. The allowed luminosity/temperature range of Stars C and D includes several known blue hypergiants, further reinforcing their identification as such stars based on luminosity and spectral features.*

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